Development and testing of a solar powered ice-making machine

Wan Zaidi Wan Omar*[1], S Mohanaruban[1], A Belhocine[2], Nazri Nasir[1], Norazila Othman[1], Tholudin Mat Lazim[1]

[1]Aeronautical Engineering Laboratory UTM,
Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

[2]Faculty of Mechanical Engineering,
University of Sciences and the Technology of Oran,
L.P. 1505 El-MNAOUER, USTO 31000 ORAN Algeria

* Corresponding author's e-mail: wanzaidi@utm.my

Abstract. *This paper reports on a design, develop and test a solar powered ice making machine project. Utilization of the solar thermal energy is selected as the power source for the refrigeration cycle due to its abundance and also low cost. Adsorption refrigeration system could be used when electrical energy is scarce, such as in rural community and is space systems. It could be powered by solar thermal energy. It is simple in construction, corrosion resistant and could utilise wide range of heat sources. Activated carbon was used as the adsorbent due to its high porosity and can withstand higher temperature. The refrigerant used for the system was methanol, which has high latent heat of evaporation and environment friendly. The system consist of three parts; generator, condenser and evaporator which consist of no moving parts except two ball valves for charging process. The goal of the system is to produce 1 kg of ice. The system was exposed to sunlight and tested for its cooling power. Results showed that the cooling process lasted for 2 hours producing cool water at 4°C. The main reason for the decrease in cooling capacity is due to the generator design, which had caused a problem in mass transfer of methanol vapour to the generator during adsorption process.*

Introduction

The electricity supply in rural areas in Malaysia and many less developed country, mostly depends on diesel generator due to unavailability in grid electricity. Moreover, the demand for refrigeration is increasing currently due to its utilization in food preservation and rural community does not have access to conventional vapour compression refrigeration as they require large consumption of electrical energy.[1] Therefore, the utilization of solar thermal energy to power the refrigeration cycle is studied. Then a solar refrigeration system that is capable of producing ice was designed, constructed and tested.

Malaysia is suitable place for solar thermal refrigeration system as we receive a monthly average solar radiation between 400-600 MJ/m$^{2.}$ [2]. Many methods of utilizing this solar thermal energy into cooling systems were researched, but the most promising way is the adsorption refrigeration system.

Adsorption system is more favoured due to its suitability in intermittent cooling system where the system has wide range of operating temperature, requires no additional electricity, less maintenance and also cost saving due to its simpler system[3]. The cooling effect is produced by adsorption system when the refrigerant is adsorb and desorb by the solid adsorbent [4]. The adsorbent-adsorbate pair commonly used in adsorption refrigeration system is activated carbon-methanol, because it has low desorption and adsorption temperature and is also non-corrosive to most metals.[5] Methanol is also often used as refrigerant in ice making system compared to ammonia and water due to its non-toxic properties and the pair can produce cooling temperature below 0°C [5].

In comparison with common vapour compression refrigeration, the activated carbon replaces the compressor by using solar thermal energy to increase the pressure of the refrigerant and also to store the refrigerant during night cycle. The pressure drop of the refrigerant during the expansion cycle, basically replaced the expansion valve in the normal compression system. This is imitated by cooling the generator bed in this system, which produces a pressure difference between the evaporator and the adsorption system [4]. Moreover the adsorption system could be conveniently adapted to different types of solar collectors such flat-plate collectors and parabolic trough collectors due to its wide range of heat source temperatures. However, parabolic trough collector was selected due to its capability of producing high temperature in short period. [6]

Methodology

Figure 1 shows the preliminary design of the solar powered ice-making machine. The solar refrigerator consists of (1) the solar generator, (2) a condenser, (3) an evaporator (4) ball valves (5) water tank and (6) insulation where. In this system, there is no throttling valves and pump, which makes the operation of the system simple.

The solar generator consists of a steel tube 2 m X 60 mm diameter, filled with activated carbon. A parabolic trough reflector, with an aperture of 2.0 m X 0.75 m, collects the sunlight and reflects it onto the tube, thus heating the tube and the activated carbon inside the tube. This increases the pressure and the temperature inside the tube to the extent the methanol would evaporate and be expelled from the tube into the condenser. The amount of activated carbon and methanol used were 0.53 and 2.5 kg respectively.

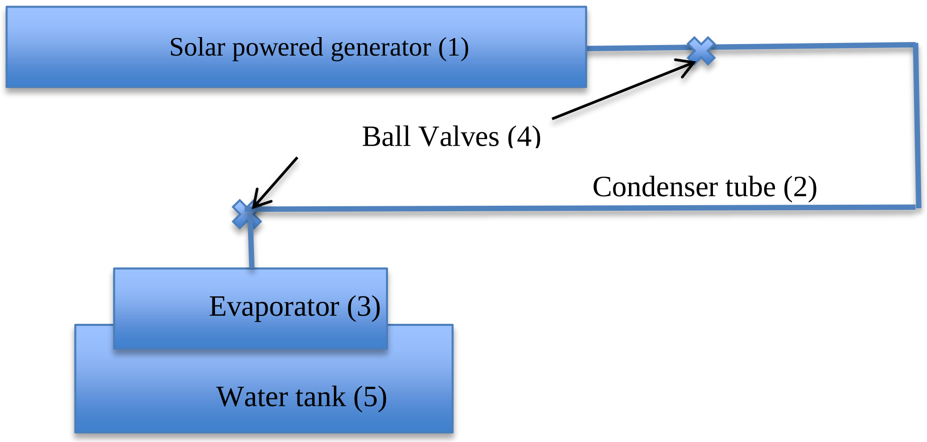

Figure 1: The schematic arrangement of the solar powered ice-maker

The working principle of this solar powered ice-making machine starts in the beginning of the day. The generator is heated by the solar radiation, which is then transferred to the activated carbon that causes the temperature and the pressure of the methanol to rise. When the activated carbon reaches the desorption temperature, the methanol vaporizes and desorb from the activated carbon. The desorbed methanol vapour would be condensed into liquid into the evaporator by the condenser. The desorption comes to an end as it reaches the maximum desorption temperature.

As the night cycle begins, the temperature and pressure of the generator reduces. This condition would cause the activated to adsorb back the methanol vapour from the evaporator. The cooling effect is produced when the methanol in the evaporator vaporizes, extracting heat from the water, and ice is formed in the insulated water tank. Figure 2 shows the Clayperon Diagram, showing the pressure-temperature thermodynamic process cycle for the system.

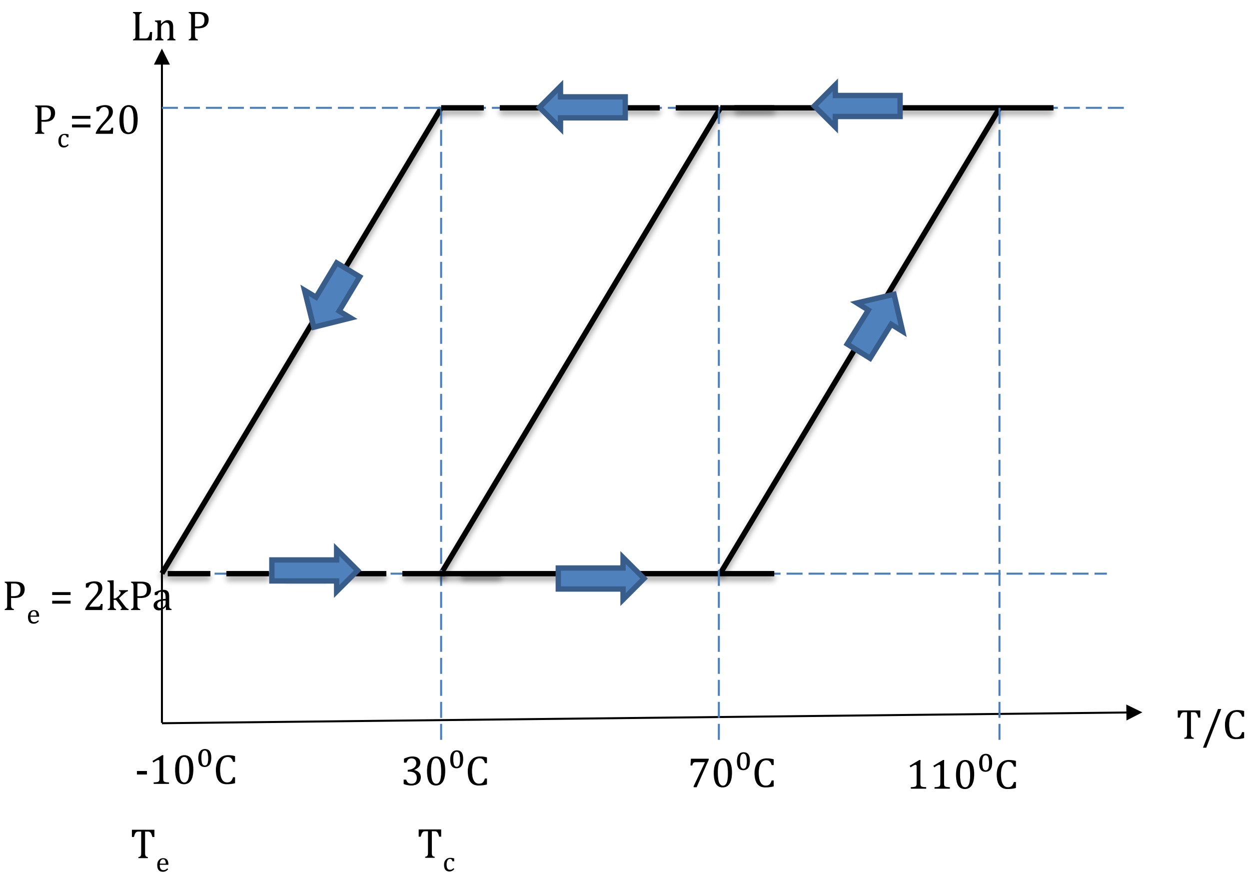

Figure 2. The solar powered ice making machine cycle in Clapeyron diagram

The analysis of heat transfer in the system is done based on the Clapeyron diagram to determine the heating amount required and also the cooling provided by the system to make the ice. Then the total heat requirement for desorption of methanol from the activated carbon, that is from point A to point B and then on to point C, is

$$Q_T = Q_H + Q_G \quad (1)$$

where

$$Q_H = (C_{VC}m_C + C_{VM}m_M + C_{MET}m_{MET})(T_B - T_A) \quad (2)$$

and

$$Q_G = (C_{PC}m_C + C_{PM}m_M + C_{MET}m_{MET})(T_B - T_A) + Q_H \Delta x m_C. \quad (3)$$

The heat released to produce cooling effect by the methanol is

$$Q_{REF} = \Delta x M_C L_M \tag{4}$$

But the net heat transfer for methanol to produce cooling effect will be

$$Q_{NET} = Q_{REF} - Q_{EVAP}, \tag{5}$$

where Q_{EVAP} is the heat released when the temperature of condensed methanol drop from condenser temperature to evaporating temperature.

$$Q_{EVAP} = \Delta x m_C C_{PM} (T_c\text{-}T_e) \tag{6}$$

Q_{ICE} is the heat energy released from water to produce ice

$$Q_{ICE} = m_W (L_i + C_{PW}(T_A - T_{fw}) \tag{7}$$

RESULTS AND DISCUSSION

Figure 3 shows the tempertures recorded during the test conducted of the prototype of the ice-making machine during the charging and evaporation or the ice formation phases. The charging occurs during the day, and the evaporationor the cooling process would normally occur during the night.

Figure 3 shows that the temperature of the generator increased from the ambient temperature early in the morning to about 82 ^{O}C after mid day. Then after about 15.30 hour, the teperature starts to drop, until it reaches ambient temperture at about 18.00 hour.

Meanwhile the temperature of the evaporator was constant throughout the day, and continue to be so through the night until about 00.30 hour. After this time, the cooling process started, and the evaporator started to cool down until 4 ^{O}C, at 02.30 hour.

It was also noticed that the heat of the gas when flowing out of the s=absorber reached 82 ^{O}C, but by the time it reached the evaporator, the tempaerature ahd dropped to 324 ^{O}C. This shows that the pipe radiator is good enough tp dump heat from the system fluid in the charging stage. And during the cooling process, the absorber temperature hardly rises. Again this shows that the pipe radiator was able to absorb enough heat to make the metahnol reaches room temperature by the time it reaches the abrober tube.

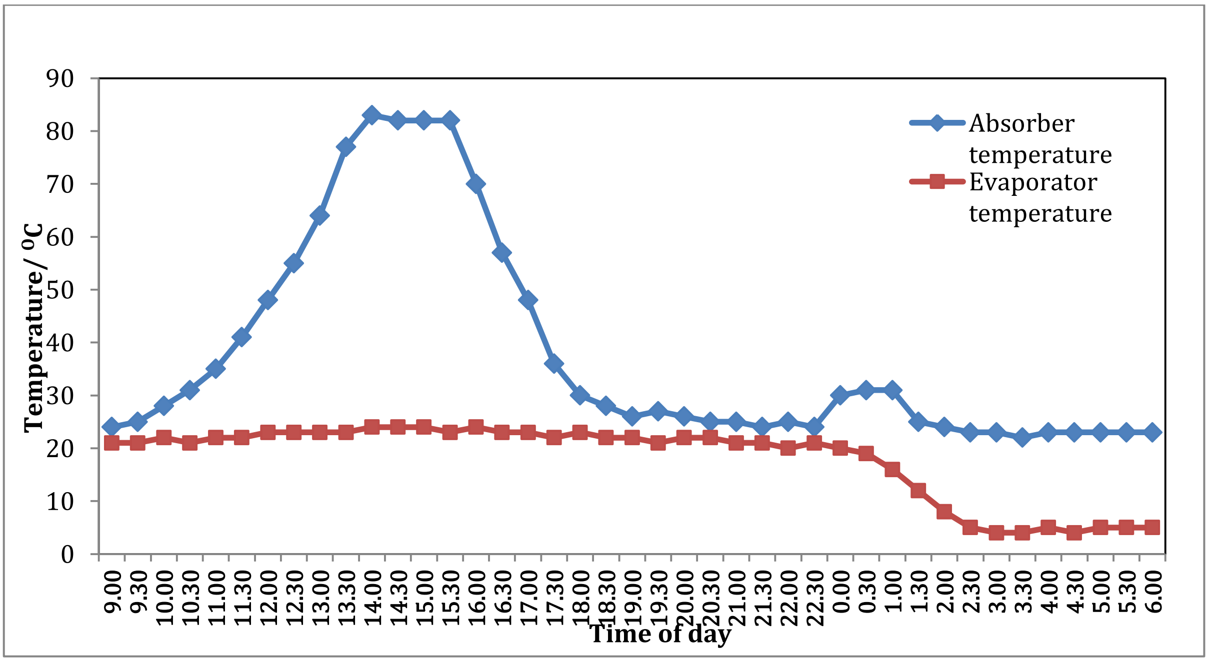

Figure 3. Temperature-Time profile of the system

Our initial absorber was construxted without the core tube. During the cooling process, it was noticed that the generator tube near the entrance was quite hot, but the other part of the tube was just at room temperature. Thus it was deduced that the methanol was adsorbed into the activated carbon in the immediate vicinity of the entrance point into the generator. This had caused congestion, limiting further adsorption flow of the methanol into the generator. This congestion had limited the cooling effect in the evaporator. Due to this problem, ice could not be produced in this test, but cooling was achieved in the water from 30^{o}C to 16°C.

This problem was solved by modifying the generator such that a central porous inner tube be inserted into the generator. This central tube helped distribute the adsorption of the methanol into the activated carbon through the whole length of the generator.

Figure 4 shows that the pressure in the system increases as the methanol inside the evaporator started to evaporate. However, the pressure of the system became constant after 45 minutes indicating that the evaporation process in the evaporator had stopped at 10kPa, although the system was designed to have a high pressure of 20 kPa.

The authors are of the opinion that the problem could be solved as explained, and a better result would be reported once the test of the modified system is conducted.

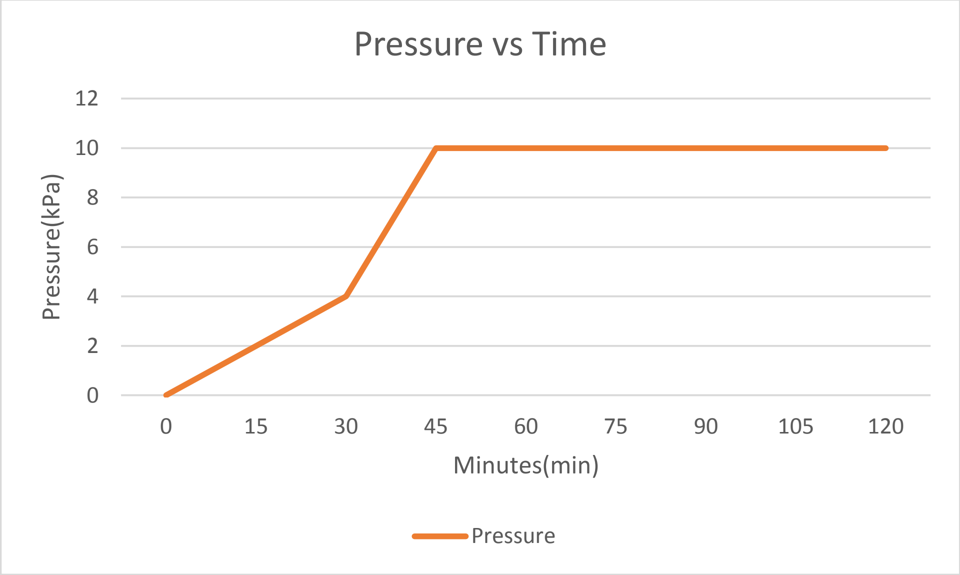

Figure 4. Pressure time trace of the system during the cooling process

CONCLUSION

The main aim of this paper is to develop and test a solar powered ice-making machine that was able to produce a minimum 1kg of ice. The solar powered ice-making machine was constructed and tested for its cooling power. In this particular test, the solar ice-maker could not produce the required ice due to the design of the generator which causes the cooling process to stall, before ice could be formed.

The generator design was a steel pipe packed with activated carbon. After some deliberation, it was surmised that the mass transfer of the methanol during the adsorption/cooling process was obstructed when the activated carbon at or near the inlet of the generator adsorb methanol vapour. At this point, the maximum concentration of methanol vapour adsorbed by the activated carbon occurred at the inlet of the generator. This phenomenon prevents the further transfer of the methanol vapour further into the generator pipe, causing the cooling effect to reduce, leading to the failure to produce ice. However, the evaporator was able to produce the desired cooling effect, producing a water temperature of 16^{o}C in a period of 2 hours.

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Nomenclature

C_V	specific heat at constant volume, kJ/kg
C_P	specific heat at constant pressure, kJ/kg
M	mass, kg
QH	heat of desorption, kJ/kg
Δx	ratio of desorbed methanol, kg/kg
T	temperature, °C
Q	heat energy, kJ
QL	latent heat, kJ/kg

Subscripts

C	activated carbon
M	Methanol
MET	Metal
w	Water
F	Freezing point
I	Ice